Gecko Mobility Aids for a Common Habitat Architecture

Robert L. Howard, Jr., Ph.D.[1] and Stephen McNierney[2]
NASA Johnson Space Center, Houston, Texas, 77058, United States of America

Cade Shuck[3] and Sebastian Boal[4]
Rhode Island School of Design, Providence, RI, 02903, United States of America

Harry L. Litaker, Jr.[5]
Leidos Incorporated, Houston, TX, 77598, *United States of America*

Denys Bulikhov, Ph.D.[6]
GeoControl Systems Incorporated, Houston, TX, 77054, *United States of America*

Spacecraft large enough for crew to move around inside them have traditionally used handrails and foot restraints to enable crew mobility. The mass of this hardware can become significant in large spacecraft such as the Common Habitat. Additionally, handrails and foot restraints in a multi-gravity habitat are trip hazards when the habitat is in a gravity environment. Further, ISS crew have noted risks of breaking ankles and wrists when using handrails for translation and have noted places where not enough handrails are present. Robotic gecko-derived grippers developed by JPL to retrieve satellites can be adapted to crew-worn pads that can adhere to surfaces to enable crew translation in microgravity. This technology will help to eliminate the need for handrails and foot restraints for mobility in crewed microgravity spacecraft cabins. It has the potential to achieve significant mass reductions in future space habitats, with application to suborbital flight, LEO, cislunar space, interplanetary space, the Moon, and Mars. Additionally, it can prevent crew injury and discomfort. Project goals and objectives are to prepare gecko uniform prototypes for use in multi-gravity testing and conduct initial investigations into human factors of postures and motions needed for intravehicular activity (IVA) translation and restraint in multiple gravity environments, without the use of handrails or foot restraints. Gecko grippers have been tested for use as robotic end effectors terrestrially, on microgravity aircraft, and aboard the ISS. Using the grippers as a body-mounted system to achieve IVA crew mobility is a new application that has not been pursued outside of this effort. This work will continue paper studies performed by NASA student interns by developing physical prototypes of spacecraft crew uniforms with gecko-derived body-mounted grippers. Clothing prototypes may include long sleeves, short sleeves, long pants, shorts, gloves, and/or booties equipped with gecko gripper pads. Forward work is to test these uniforms in a 1g environment to verify that the design does not introduce obstructions, trip hazards, or other consequences when used in

---

[1] Habitability Domain Lead, Human Systems Engineering and Integration Division, AIAA Senior Member.
[2] Undergraduate Pathways Intern, Human Systems Engineering and Integration Division.
[3] Undergraduate Student, Department of Industrial Design.
[4] Undergraduate Student, Department of Industrial Design.
[5] Senior Human Factors Design Engineer, Human Systems Engineering and Integration Division.
[6] Senior Human Factors Design Engineer, Human Systems Engineering and Integration Division.

terrestrial gravity. Based on the 1g test results, the uniform prototypes will be refined, and a test plan developed for testing at 0g, 1/6g, and 3/8g.

I. Introduction

A. Common Habitat overview

The Common Habitat is based on the use of the SLS core stage liquid oxygen (LOX) tank as the primary structure for the pressure vessel. [1] This is a similar approach to that taken in the 1970s with the construction of the Skylab space station from the Saturn S-IVB liquid hydrogen propellant tank. Unlike Skylab, which was designed exclusively for use in the microgravity environment of Low Earth Orbit, the Common Habitat features a design intended to be equally applicable for use in microgravity, 1.6g, 3/8g, and 1g. The Common Habitat has a horizontal orientation and is divided into three decks, an upper deck, mid deck, and lower deck, with sufficient habitation accommodation for a crew size of eight. [2] An exterior image of the Common Habitat and views of its three decks are shown in Figure 1.

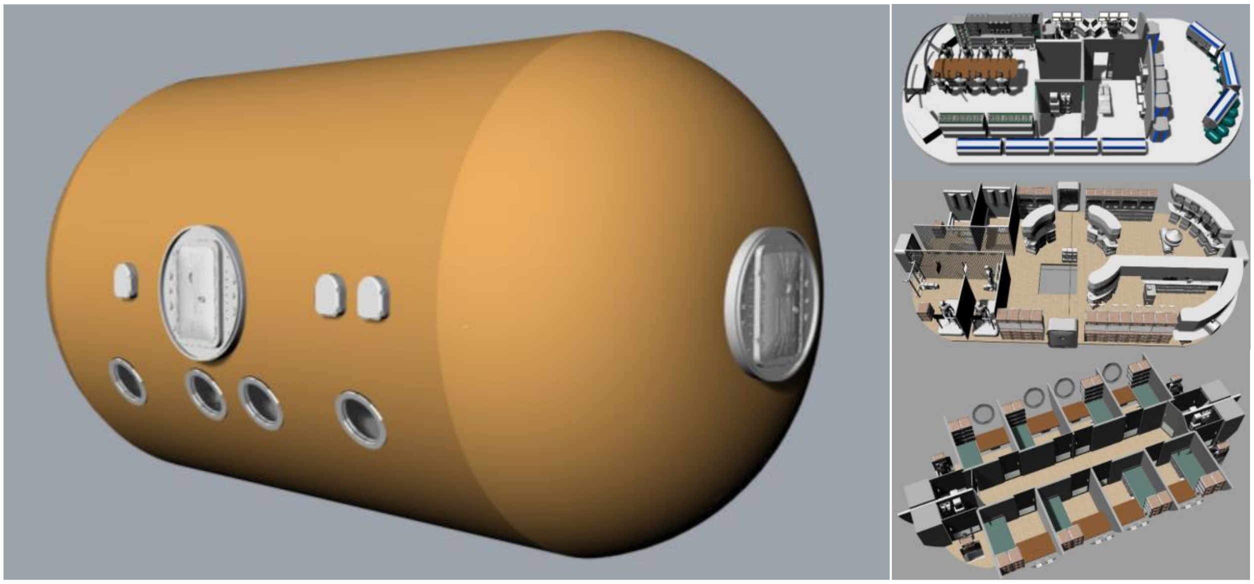

Fig. 1 Common Habitat

The Common Habitat is not part of the current NASA reference architectures for exploration of the Moon and Mars. It is instead an ongoing study of potential options that – should viability be demonstrated – could potentially be applied to human exploration programs.

B. Challenge of Restraints and Mobility Aids

The multi-gravity nature of the Common Habitat poses challenges for crew mobility aids and restraints. Historically, crew mobility and restraint has been addressed in spacecraft through the use of handrails and foot restraints, such as those used on the International Space Station (ISS) and shown in Figure 2 and Figure 3.

Fig. 2 Handrails on the International Space Station

Fig. 3 Foot Restraints on the International Space Station

The use of handrails and foot restraints uses muscles and triggers forces and reactions associated with several key parts of the body. Translation or relocation via handrails involves primary movement with the fingers, hands, arms, and shoulders. Secondary movement is achieved with toes, feet, legs, stomach, and back. [3] Station keeping is primarily achieved via toes, feet (tops), legs (shin), stomach, and back. Fingers, hands, arms, and shoulders are secondary. [3]

Some concerns have emerged regarding the handrails and foot restraints aboard the ISS. The Flight Crew Integration (FCI) Operational Habitability (OpsHab) team maintains the FCI ISS Crew Comments Database (CCDB), which contains crewmember comments from the ISS Post Flight Debriefs. CCDB data reports generated from the CCDB do not represent or replace an official crew office position or consensus. The content of the CCDB reflects individual crew opinions and are not to be interpreted as Astronaut Office position or consensus.

By definition, handrails and foot restraints are limited to specific placement within the habitable environment and cannot literally be everywhere a crew member might venture. Some ISS crew have felt that the handrails were not always in the places where they wanted them.

Possible injuries ISS crews could experience associated with both handrails and foot restraints, including back pain, shin splints, stress fractures, tendinosis or tendinitis, and compartment syndrome. Several crew members have noted in debriefs that when moving about the space station, when attempting to catch a handrail, especially if moving quickly, they can get their foot or wrist in an awkward position that places them at risk of a fracture. Some crew believe it is inevitable that eventually such an injury will occur.

Reduction of crew injury risk is of increasing importance as missions travel farther from Earth. A broken wrist or ankle within the latter few months of a transit to Mars could result in an inability to conduct surface operations and a loss of mission objectives. Such an injury towards the end of the return to Earth could result in an inability to safely egress Orion following splashdown, which in a worst case could lead to loss of crew. Until now, the previously mentioned handrails and foot restraints have been accepted as the only alternative.

Crew also commented a variety of usability concerns associated with extended use of the handrails, including handrails not necessarily in the desired orientation, comfort of using the handrails, callouses, red marks, soreness and other discomfort even to the point of blistering and bleeding.

Additionally, given the common design philosophy of the Common Habitat architecture (identically manufactured and outfitted habitats in both microgravity and gravity environments), handrails and foot restraints are fundamentally unsafe. These restraints and mobility aids become trip hazards in the presence of gravity and would therefore be unacceptable for use in a Moon or Mars base camp.

A crowdsourcing campaign was launched in the summer of 2020 to pursue solutions for a common restraint and mobility aid system that works in four gravity environments (0g, 1/6g, 3/8g, and 1g) with no reconfiguration across the different gravities. [4] One of the finalists proposed the idea of footwear augmented by five pneumatically or hydraulically actuated gecko gripper pads. [5] This concept served to inspire additional work that led to the current iteration of the Gecko Mobility Aids, which has been pursued as part of the volunteer Common Habitat Architecture study, with the assistance of Space Grant interns from the Rhode Island School of Design (RISD).

This paper demonstrates to habitat designers, human factors personnel, and NASA Exploration Systems Development Mission Directorate personnel a means to provide crew mobility without the use of handrails or foot restraints, thereby enabling a gravity-independent spacecraft architecture. Until now, gecko grippers, the core component of Gecko Mobility Aids, have only been commercially used for robotic end effectors to grapple solar arrays and other structures not manufactured for robotic manipulation.

In addition to its application to the Common Habitat Architecture, Gecko Mobility Aids offer potential to benefit NASA spacecraft in development such as HLS, Gateway, and the Mars Transit Habitat, as well as commercial LEO platforms and suborbital spacecraft. It may also increase commonality between the Transit Habitat and Surface Habitat and will help enable future spacecraft concepts. Even reduced gravity aircraft operators may find this technology useful for their flight crews.

II. History of Gecko Grippers at Stanford and JPL

Geckos are capable of sticking to almost any surface thanks to the structure of their toes. These bulbous toes are covered in hundreds of microscopic hairs called setae. Adhesion occurs when electrons from the gecko’s hair molecules and electrons from surface molecules interact with each other and create an electromagnetic attraction. This attraction is what is known as Van der Waals forces. The force itself is inherently weak, this is the reason for the vast quantity of setae.

The mechanism by which geckos use Van der Waals forces to stick to walls has been replicated in the form of gripper pads developed by Stanford. In order to mimic the capabilities of the gecko, wedge shaped forms were made to mimic the setae of the toes. This biomimicry allowed for the design of a synthetic gecko material to be possible. The synthetic material mimics the abundance and form of the gecko’s spatula. The form of the individual “hairs” is vital to the adhesion taking place. A shear horizontal force is applied to the synthetic material in order to accumulate a sufficient quantity of Van der Waals forces. As soon as this surface area is relieved, the adhesion of the material halts. This adhesion is fundamentally insensitive to pressure, temperature, and radiation, but it is highly sensitive to dust.

Although not being directly applied to wearables, Stanford University produced a system of gecko tiles. Two 140 cm^2 tiles were mounted to the hands of the individual and allowed for a 70 kg Stanford researcher to scale a 90-degree wall in the gravity of Earth. [6]

JPL has refined the work initially performed by Stanford for use as robotic end effectors. Aaron Parness, a former JPL employee left behind significant documentation of work he performed to pioneer this technology. Current JPL engineers including Ethan Schaler and Paul Glick have continued to perfect the technology. JPL’s Gecko Adhesive Grippers use microscopic hairs that stick in one preferred direction. Using multiple pads, grippers can selectively stick to and release from surfaces, need no power in the ON or OFF states, and are reusable thousands of times.

JPL has tested the grippers on 30+ spacecraft surfaces including bladder material of inflatable habitats. They have subjected them to over 30,000 cycles, demonstrating reusability. The material is fabricated from a space-rated silicone polymer, and it does not need preloading to work. The gripper material can be used for intravehicular activity (IVA) or extravehicular activity (EVA). JPL developed a test article for initial demonstrations of the gripping material, shown in Figure 4.

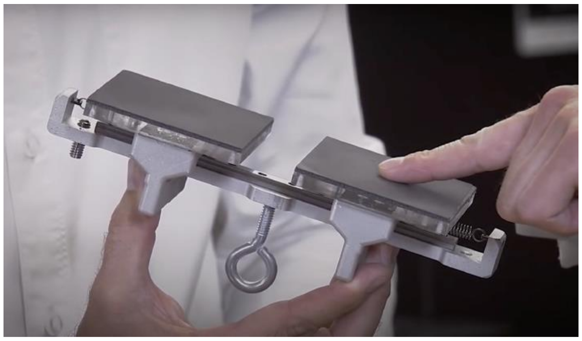

Fig. 4 JPL Gecko Gripper Prototype.

Two plates of the material are placed onto a surface and the shear force is applied, turning the gripper "on" as shown in Figure 5. This force is primarily maintained through tension springs. The adhesion of the gripper is turned "off" by relieving the tension.

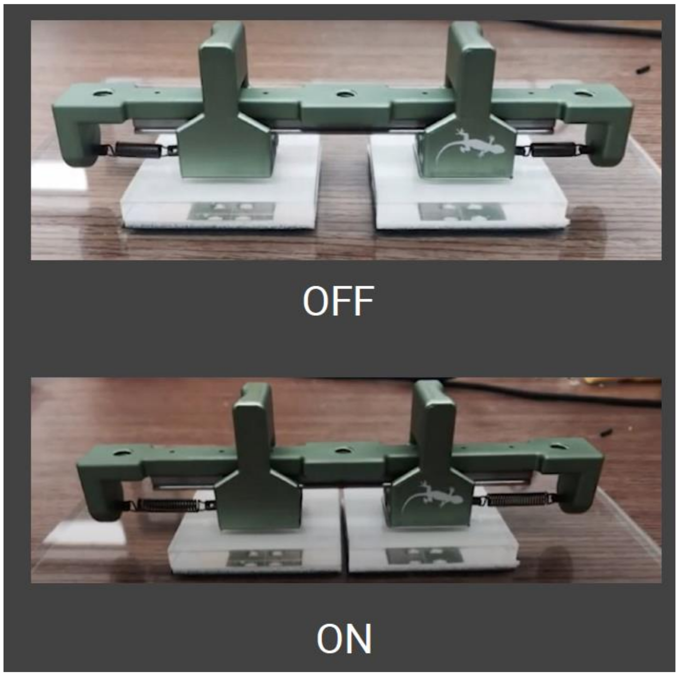

Fig. 5 Gripper Prototype On/Off Configuration

The original goal of the JPL team was to develop the technology to conduct swift removal of space debris, but the team has indicated that it could lead to many future uses, including crawling inspection robots, cubesat and free-flyer docking/landing gear, satellite servicing & debris removal end-effectors, factory floor applications, and presumably several more.

Astronaut Jeff Williams performed the first in-space experiments with Gecko Grippers, as seen in Figure 6. The data correlated well with ground tests in the lab, validating the adhesive's performance in space. JPL has envisioned extending this technology to climbing robots and anticipates it may also prove useful for grasping, anchoring, and medical applications. [7] Two Astrobee robots launched to the International Space Station in 2019 were equipped with gecko grippers to allow the robots to perch on smooth surfaces. [8]

Fig. 6 Astronaut Jeff Williams Performing the First In-Space Experiments with Gecko Grippers

III. Application of Gecko Grippers to Crew Clothing

The research discussed in this paper adapts these gecko gripper pads to crew clothing items to enable crew to maneuver about spacecraft in microgravity but still be able to operate without obstruction in lunar or Martian gravity. This will limit the need for handrails and foot restraints in human spaceflight. Replacing handrails and foot restraints with gecko gripper augmented crew clothing is intended to reduce vehicle mass. Not only is the sheer number of mobility aids dramatically reduced, but clothing-based gecko grippers are anticipated to be lighter than ISS handrails. They also eliminate trip hazards in gravity environments by eliminating handrails from the deck flooring. And finally, they reduce potential for crew injury in microgravity, including broken ankles and wrists, by eliminating the potential to catch a hand or foot in a handrail while moving at speed, because there are no longer any such handrails.

In order to be effective, crew-worn gecko grippers would need to be effective for translation and station keeping in microgravity or very low gravity but are not become hazards or otherwise in the way when in full or higher fractional gravity. For instance, they should enable a crew member to walk in microgravity but not cause one to trip in Mars gravity. Gecko-based translation aids should allow crew to maneuver throughout the habitat in all directions.

In an artificial gravity case, an artificial gravity habitat might spin up from 0g to a fractional g or 1g. Then, at a subsequent point in the mission it might spin back down to 0g. The translation aids should work in 0g and throughout gravity transition process until the gravity increases to the point where they are no longer necessary, at which point they should not be an encumbrance.

After locating JPL personnel who had conducted the previously mentioned gecko research, RISD students were able to obtain from JPL several material coupons for initial testing. The JPL samples were taken to Brown University and subjected to electron microscope imaging. This helped the team better understand the nature of the gecko gripper material. As can be seen in Figure 7, the material is composed of extremely small ridges. The imaging had the unexpected effect of also revealing how easily the material can trap debris particles. Cleaning the gecko grippers is an area of future work that will need to be addressed once their nominal viability as crew mobility aids is established.

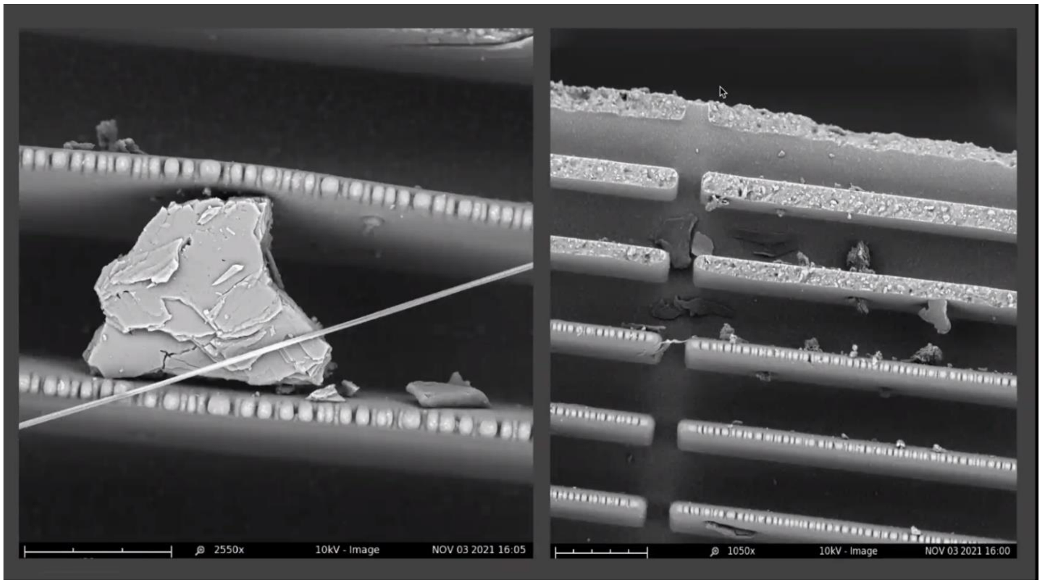

Fig. 7 Brown University Electron Microscope Gecko Material Imaging

One of the RISD students then used the sample material to create a low fidelity prototype of a gecko gripper-equipped glove, shown in Figure 8. He used this preliminary glove to experiment with how to adhere the gecko material to a flexible surface and piloted simple tests using the glove to create and adhesive force on a transparent, plastic plate, shown in Figure 9. The plate demonstration revealed some adherence but likely did not fully test the material's ability to adhere. There was also some uncertainty about how to best test in a gravity environment.

Fig. 8 Preliminary Gecko Glove

Fig. 9 Glove Plate Demonstration

IV. Gecko Uniform Concepts

Considering the anticipated crew experience in spaceflight, a variety of uniform items were identified for augmentation with gecko grippers. With no handrails or foot restraints on the spacecraft, crew will need to be able to utilize the gecko system regardless of how they are dressed.

Through the design process the team became interested in utilizing the gecko material on anchoring points of the body. This process was initiated with the functional mapping of determined points of contact. This process grew into the design of a standardized suit that has the gecko gripping material integrated within itself.

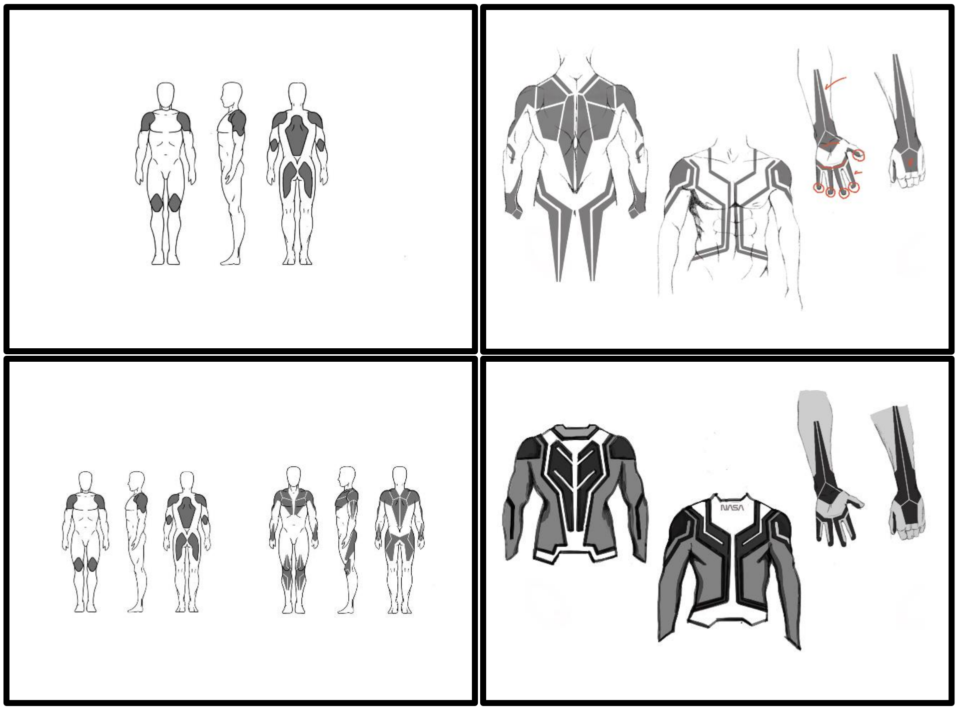

Fig. 10 Upper and Lower Body Initial Mapping of Points of Contact

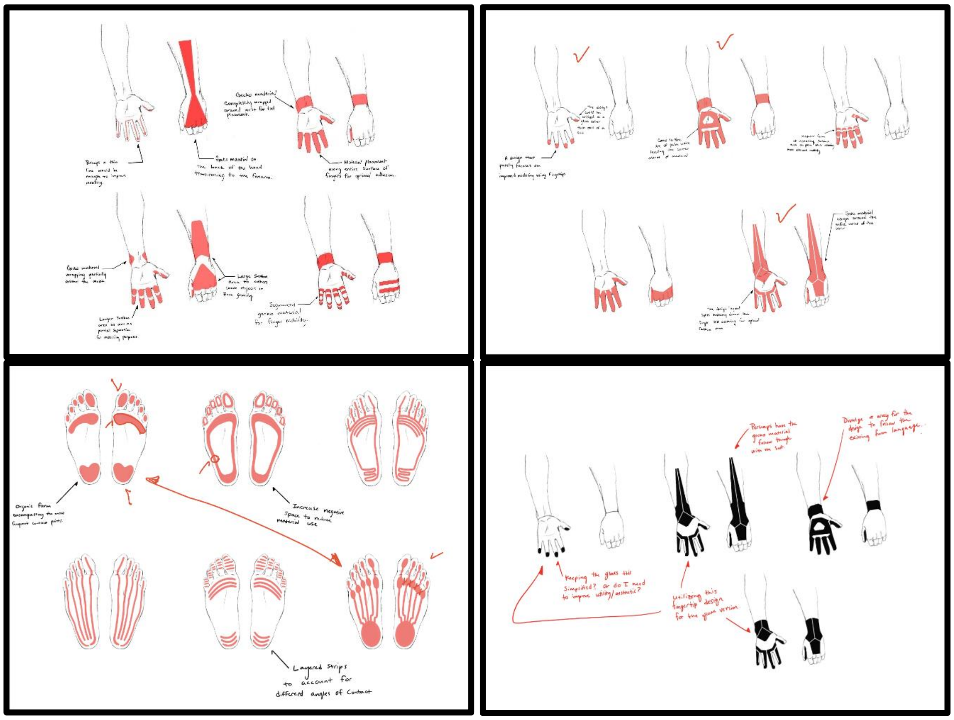

Fig. 11 Hand and Foot Initial Mapping of Points of Contact

Due to variation in cabin temperature, both long and short sleeves and long pants and shorts are available to the crew. It is also possible that the short sleeves and shorts could be used during crew exercise. Additionally, some form of footwear is needed. Gloves are also identified as a clothing option of interest.

With this in mind a set of male uniform items were modeled as an initial starting point. The designer considered historic astronaut IVA clothing but was not held to replicate the current look and feel of NASA flight crews. Given freedom to explore crew fashion, an alternate styling was proposed. It should be noted that a as an initial baseline, the crew uniforms are based on a white color scheme, but these uniforms could be implemented in any color as a matter of crew preference, or could utilize color to denote specific crew specialties, missions, destinations, or spacecraft. Additionally, the shirts notionally feature a NASA logo, nationality shoulder flag, and chest name badge and wings, but additional patchwork could identify missions, spacecraft, or other designations. The black coloring is stylistic, but also denotes general locations of gecko pad material.

1. *Long Sleeve Shirt*

The long sleeve shirt includes gecko pads on the shoulders, elbows, and back, as well as narrow gecko strips on the chest and around the waist. The shoulder pads are intended to allow a crew member to hold themselves in place against a surface such as a wall. It is likely they will need to be used in conjunction with gecko pads on some other part of the body in order to maintain a sheer force. This could be accomplished, for instance, with a left shoulder pressed against a wall and a right foot pressed against a floor.

The elbow shoulder pads allow for multiple options. A single elbow pad can be used in conjunction with gecko pads on other parts of the body in a manner similar to the elbow pads. Two elbow pads together can be used to anchor a body, such as against a table surface. Additionally, two elbow pads in conjunction with knee or bootie pads can be used to crawl against a surface.

The back pads are intended to allow a crew member to hold themselves in place against a flat surface, such as a chair or seat back. It is possible the back pads could be used alone by flexing the back to create a shear force. It is also possible the back can be used in conjunction with gecko pads on other parts of the body such as booties or backs of the thighs.

The narrow gecko strips on the chest and around the waist can be used to attach small instruments and other handheld devices, provided they are equipped with spring-loaded surfaces or other mechanisms capable of triggering the shear force needed to adhere to the gecko strips.

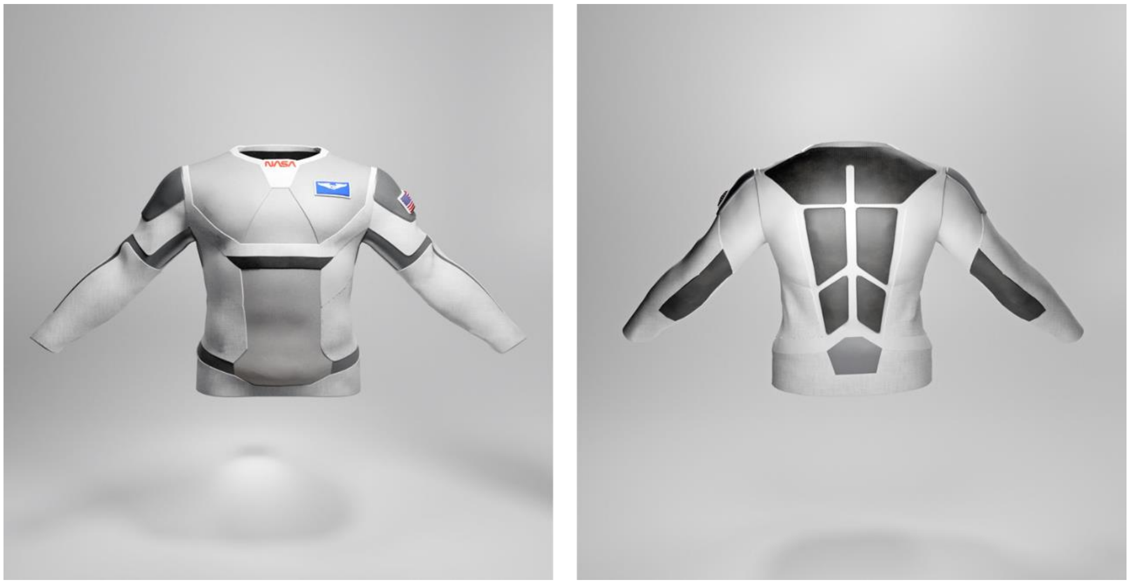

Fig. 12 Long Sleeve Shirt

2. *Short Sleeve Shirt*

The short sleeve shirt is similar to the long sleeve. It has gecko pads on the shoulders and back, as well as smaller pads on the sides just above the hips and a narrow strip on the chest. The shoulder, back, and chest gecko material is identical in function to those on the long sleeve shirt. The pads on the sides can be used similar to the narrow gecko strips to anchor devices. In conjunction with gecko material on other parts of the body they may also be used in some cases to anchor the body.

Fig. 13 Short Sleeve Shirt

3. Long Pants

The long pants include gecko pads on the knees and back of the thighs, with narrow gecko strips around the waist. The knee pads can enable a crew member to hold position by using both knees to induce a shear force against a surface. A single knee could also be used in conjunction with gecko pads on other parts of the body. The knee pads can also be used in conjunction with gecko material on the hands or elbows to enable crawling against a surface. The pads on the back of the thighs can be used together to adhere to a surface, such as when sitting. When used in conjunction with the pads on the shirt back a more secure seated position may be obtained. The narrow strips on the waist can be used identically to their counterparts on the shirts to attach small instruments or other handheld devices.

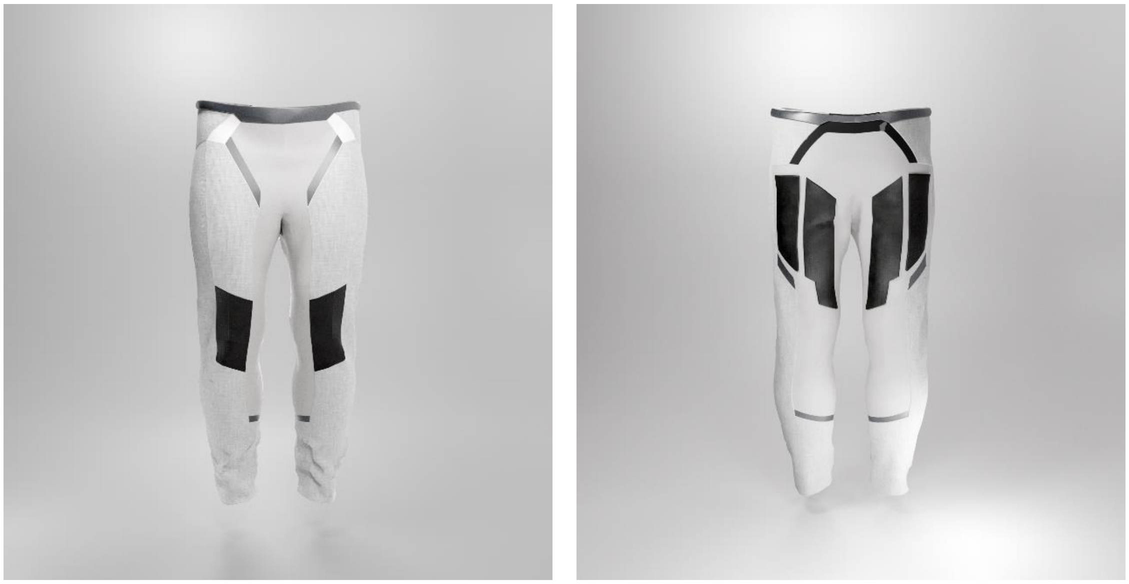

Fig. 14 Long Pants

4. Shorts

The shorts have gecko pads on the buttocks and back side of the thighs. There are strips on the front waist and the front of the thighs. The gecko pads on the back of the thighs and buttocks can be used identical to the pads on the back of the thighs of the long pants. Like the narrow strips on other clothing items, the strips on the front waist and front of the thighs are used to attach small instruments or handheld devices.

Fig. 15 Shorts

5. Gloves

There are three variants of hand-worn gecko-equipped clothing – thimbles, standard gloves, and gauntlets. The thimbles are the lightest and least intrusive of all of the gecko-equipped clothing. Ten thimbles cover only the fingertips, with gecko material coating the underside of each thimble. Intended to be the least obtrusive mobility aid, the thimbles can be used alone for translation and stabilization, or in conjunction with gecko pads on other parts of the body.

Fig. 16 Thimbles

The standard gloves are functionally identical to the thimbles but are complete gloves. It is suspected that the gloves may stay on the hand more comfortably than the thimbles, which may or may not develop a tendency to slide off the fingertips.

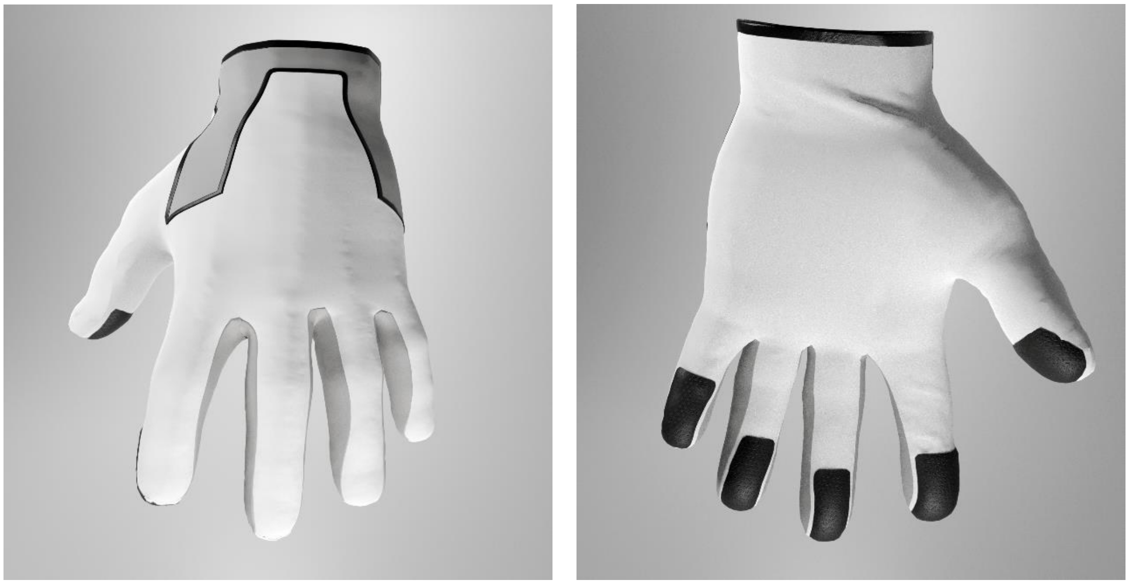

Fig. 17 Standard Gloves

The gauntlets add a forearm cuff and add gecko material on the back of the hand and palm. The gauntlets create more surface area for gecko adhesion than the standard gloves or thimbles. Additionally, the gecko material on the back of the hand allows for an alternate translation posture, one that could potentially be used while carrying something in the hand.

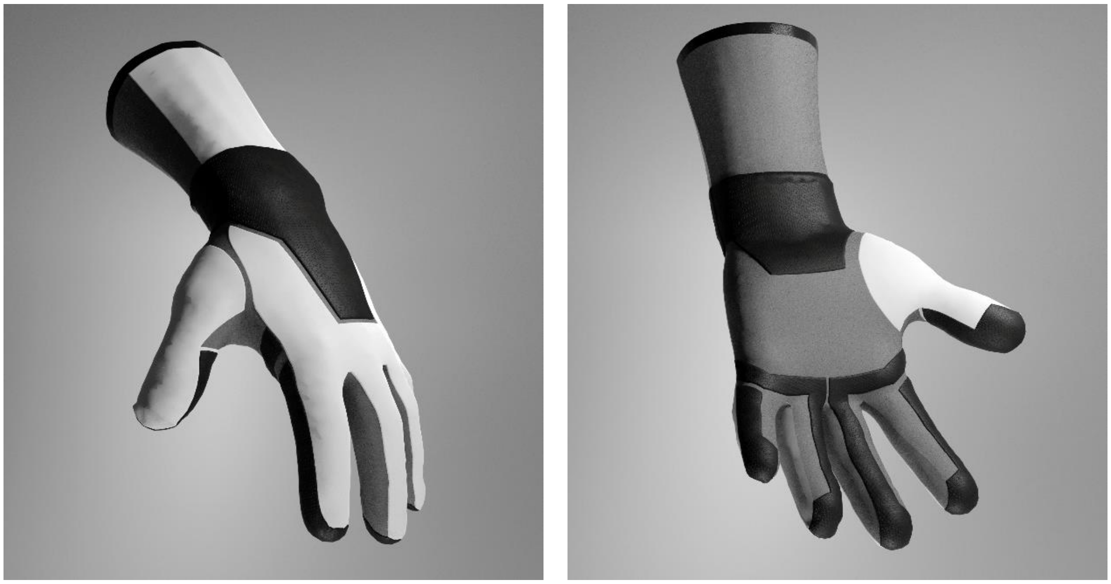

Fig. 18 Gauntlets

6. *Booties*

The booties are a sock-like foot cover that are thin enough to allow the feet to flex as needed to create shear forces with the attached gecko material. There are three variants of the booties that allow for experimentation to refine the ultimate concept. It may also prove that these variants may each be suited to different crew activities.

The first bootie is the most lightweight of the three. Each bootie consists of four narrow strips of gecko material.

The second bootie is the variant with the most gecko material. The entire forefoot and heel areas are covered with gecko pads and narrow strips line the entire length of the foot. Only the arch area is not equipped with pads. This variant will provide the most adhesive force of the three variants.

The third bootie has an intermediate level of gecko coverage. Gecko material covers each of the toes, the ball, and the rearmost portion of the heel.

With all three variants, both feet can be used together to hold the crew member in place. Sliding or twisting the feet against a surface in opposing directions can create a shear force to activate the gecko material's adhesion. It is also possible that a crew member may be able to walk after a fashion in microgravity using only the booties. Several methods may be possible, one of which creates a shear force by scrunching the toes towards the ball of the foot on one bootie, while relaxing the other and relocating the second bootie in the direction of travel. Alternately, a shuffling motion might be possible based on the previously mentioned posture used to hold the crew member in place. With practice, a crew member may be able to relax the shear force long enough to reposition one foot in the direction of travel and reinstate the shear force before losing contact with the surface. Alternately, the gloves or gecko material on the elbows could be used in conjunction with the booties to enable translation.

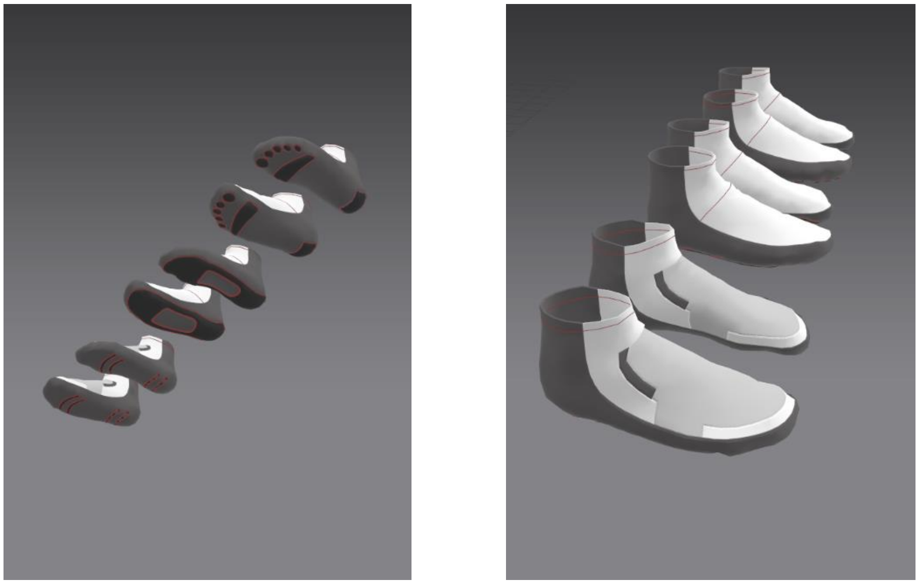

Fig. 19 Booties

V. Preliminary Testing

Based on the previously mentioned Stanford gecko tiles that were capable of supporting 70 kg with 280 cm^2 of tile surface, a possible gecko adhesive 1g performance of 0.25 kg/cm^2 is estimated, which translates to a force per unit area of roughly 2.45 N/cm^2. [6] Estimating a typical surface area of a fingertip at 2.25 cm^2 and given linear scaling, a test subject using a single gloved hand should be able to exert a force of roughly 28 N, which is approximately 4.4 times the 6.23 N force of a single Manned Maneuvering Unit cold gas thruster. [9] Thus, hand-based control for an IVA crew member should be achievable with a gecko gripper-derived system. This might suggest the larger pads may actually produce greater adhesion force than desired. It is not clear, however, if the Stanford gecko material is equivalent to that produced by JPL. Nor is it clear if the adhesive force will scale linearly with size. Hence, there is a need for initial testing to refine the desired gecko adhesive material.

A key research goal is to gain an understanding of how best to cause the gecko grippers to engage and disengage. There is very limited data on the activation of gecko adhesion through biomechanical forces. The JPL gripper concepts utilized springs or other robotic mechanisms. It is not clear how easy, tiring, or repeatable human activation will be. The gecko material works when a shear force is created, which in this case must be done by the human. It will only adhere as long as the shear force is maintained. The most intuitive way to create the shear force is by contracting muscles to slide the gecko material against a surface. But is it better to create the shear force by contracting muscles or by relaxing them?

How will the selected clothing work for or against the gecko grippers? How tightly do the clothes need to adhere to the body? Clearly, baggy clothing would not be viable as the body could not transmit a force through them to create a shear force. But how tight do they need to be in order to be effective? Is the answer different for different articles of clothing? For instance, a pair of gloves generally has a tighter fit than a shirt or long pants. Will they be equally effective?

Where it is possible to cause a given gecko gripper to engage or disengage, a question remains as to how tolerable that action will be for the crew. Is it comfortable? For instance, it may be possible to create an adhesive force on the booties by scrunching the toes, but this may be tiring to sustain or uncomfortable to perform repeatedly. More concerning, would any actions to engage or disengage place the crew member at risk of injury? Will natural walking motion engage and disengage the grippers or will crew need to learn a new way to walk?

A NASA Innovation Charge Account (ICA) grant was awarded to fabricate a prototype set of clothing items with gecko gripper pads attached. Due to limitations in the ICA funding level, some modifications to the uniform concept have been implemented for this initial prototype set. The Jet Propulsion Lab produced 44 gecko gripper pads, each of which are roughly 4-inch diameter disks. The team used the disks as-is for the shirts, shorts, and long pants instead of cutting them to match the designs in the initial concept. Socks were used as the booties, but with a significantly more simplified gecko design than shown in Figure 19. Gecko pads were cut to simple, customized patterns for the socks, gloves, gauntlet, and thimbles.

Uniform shirts included the NASA logo, an American flag, and the Gecko Mobility Aids project patch, shown in Figure 20.

Fig. 20 Gecko Mobility Aids Project Patch

C. Laboratory Testing

The conclusion of the ICA project was a prototype crew uniform test in a 1g (laboratory) environment. This testing conducted initial investigations into human factors of postures and motions needed for IVA translation and restraint in multiple gravity environments by means of body-worn gecko-derived gripper pads, without the use of handrails or foot restraints. The goal of testing in a 1g environment prior to any reduced gravity testing was to verify that the design does not introduce obstructions, trip hazards, or other consequences when used in terrestrial gravity and to refine the placement of gecko grippers on the crew uniforms.

Testing involved simulation of use cases for both crew translation and station keeping, with slightly different test goals for each. For crew translation, based on predicted ways to move in microgravity, the 1g testing called for test subjects take on the associated postures and attempt to create adhesion forces. There was no attempt to actually move beyond that needed to take on the appropriate postures. Translation generally involved variations on walking or on crawling – with either hands or elbows combined with knees or feet.

However, should the uniform be worn in a gravity environment (e.g., while on the surfaces of the Moon or Mars) it is important that the gecko grippers not accidentally activate, or if they do that the adhesive forces should not be so great as to cause the crew member to stumble or otherwise become encumbered. It is also desired that the crew member not become a "magnet," unintentionally adhering small items to his or herself while performing daily activities. The 1g testing tested for accidental adhesion in this regard.

With respect to station keeping, the first goal was to confirm that the test subjects can activate the gecko material in postures that would allow them to maintain a fixed position in microgravity. It was deemed likely that some of the postures needed to adhere the gecko material will need active muscle effort to maintain and therefore would be tiring to continue for station keeping for extended periods of time. These postures may likely be transitional postures used while preparing for other motion or other means of restraint. However, this hypothesis can only be refined by the both the 1g and reduced gravity aircraft tests. Possibly a suborbital or more likely an orbital flight would be needed to confirm potential fatigue associated with postures. Station keeping involved an emulation of standing or kneeling (using the feet or knees), holding in place with the back, an emulation of sitting using the thighs and buttocks, and using a combination of multiple extremities (e.g., feet and back) to wedge into a corner or wall/floor intersection.

An additional goal was to ensure that when sitting or conducting other activities in gravity, the station keeping postures do not unintentionally activate, or if they do, that they not be of sufficient force to hold one in place when the intent is to get up or otherwise move around.

Multiple lessons were learned from the 1g test that will be used to refine the crew uniform design and help develop test plans for reduced gravity testing. The gripper pads were found to work best on smooth, hard surfaces. The forces were very light. They were difficult to perceive in 1g and did not interfere with motion in gravity environment. The finger cots were annoying to don/doff – they need a device to assist, making it a one-step don/doff, or they will be inferior to gloves/gauntlets. Footwear needs coverage on toes, ball of foot, and heel; coverage on the arch is also useful. Walking in microgravity is probably possible but it is likely one could easily be knocked off their feet from even light disturbances. Crawling is possible with a combination of gloves/gauntlets/finger cots and footwear. Grippers on the backside of the gauntlets can support crawling when hands are needed to hold something. Loose clothing interferes with the function of the gecko grippers (the shear force is not maintained). Lining the elbow and knee pads up with the body correctly requires a precise fit, which may be difficult to ensure. The shirt is generally only useful when in used combination with other clothing – in most cases the shirt cannot create shear by itself. Trousers are preferable over shorts and work well in combination with shirts. The thigh pads are more useful on trousers and shorts than the buttocks pads. The thigh pads can make contact with a flat surface for "seating," but the buttocks pads do not make good contact.

VI. Conclusions / Forward Work

The approach undertaken in this project followed the design-build-test methodology to iterate the gecko-uniform concept developed under student research and used the 2022 ICA funding to produce operational prototypes and subjected them to a 1g test for human factors mobility analysis. Forward work will continue to evaluate the usability and effectiveness of a crew-worn GMA system in reduced gravity, as contrasted with the robotic gecko grippers demonstrated in microgravity aircraft and aboard ISS.

The 1g test results will enable the team to refine the uniform prototypes, update test procedures, and complete a modified test plan for use in microgravity. The team will develop hypotheses for testing in a reduced gravity aircraft flight to refine the design and pending funding, based on lessons learned from the 1g test, will produce higher fidelity crew uniforms that can be used in reduced gravity testing. This evaluation of the prototypes under relevant gravity conditions will help determine if the crew can utilize the gecko grippers in lieu of handrails to maneuver within a spacecraft.

The hope is that gecko gripper uniform prototypes will be more fully tested in a follow-on series of reduced gravity aircraft flights and perhaps even in longer duration testing aboard commercial suborbital flights. NASA is in the process of forming a Suborbital Crew (SubC) project and either this office and/or other partnerships with suborbital flight providers may lead to a path for this testing. The longer duration will better verify both crew mobility and station keeping at a fixed location.

The team will continue to solicit funding grants to continue work to develop this system. Collaboration will continue with RISD and JPL but, if possible, may be expanded to include commercial spaceflight providers. Additionally, new design work is desired to produce female uniform designs. The RISD work focused entirely on a male uniform. The differences in female center of gravity as well as stylistic considerations are known drivers to produce a female-specific design. The JSC Center for Design and Space Architecture's existing partnership with the Space-Grant funded Rhode Island School of Design will likely enable this work to continue through either design studio courses or student interns. These uniforms will also be prototyped, refined, and join the male uniforms in testing.

References

[1] R. Howard, "Opportunities and Challenges of a Common Habitat for Transit and Surface Operations," in *2019 IEEE Aerospace*, Big Sky, MT, 2019.

[2] R. Howard, "Internal Architecture of the Common Habitat," in *2022 IEEE Aerospace Conference*, Big Sky, Montana, 2022.

[3] R. Behrendsen, *Ergonomics and Human Factors for the Restraints and Mobility Aids on the International Space Station*, Houston, TX: NASA, 2013.

[4] GrabCAD, "NASA Challenge: A Common Restraint and Mobility Aid System for Multiple Gravity Environments," STRATASYS, [Online]. Available: https://grabcad.com/challenges/nasa-challenge-a-common-restraint-and-mobility-aid-system-for-multiple-gravity-environments. [Accessed 18 June 2022].

[5] R. Slimani, "Gecko Feet Shoes," Stratasys, 16 August 2020. [Online]. Available: https://grabcad.com/library/gecko-feet-shoes-1. [Accessed 2 July 2022].

[6] E. Hawkes, E. Eason, D. Christensen and M. Cutkosky, "Human Climbing with Efficiently Scaled Gecko-Inspired Dry Adhesives," *Journal of the Royal Society Interface*, vol. 12, no. 102, 6 January 2015.

[7] A. Parness and V. White, "Fibrillar Adhesive for Climbing Robots," *NASA Tech Briefs*, 1 January 2013.

[8] R. Carlino, J. Barlow, J. Benavides, M. Bualat, A. Katterhagen, Y. Kim, R. G. Ruiz, T. Smith and A. M. Vargas, "Astrobee Free Flyers: Integrated and Tested. Ready for Launch!," in *International Astronautical Congress 2019*, Washington, DC, 2019.

[9] J. Lenda, "Manned Maneuvering Unit: User's Guide," Martin Marieta Corportation, Denver, CO, 1978.